MIIM LCA Ph.D. Club

LCA of Food Products and Production Systems

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Abstract. This article is a summary of my dissertation in which LCA was applied to food products and production systems. The overall objectives were: (1) to learn more about the feasibility and limitations of LCAs of systems for the production and consumption of foods (food systems); and (2) to generate information on the environmental impact of such systems. Case studies of tomato ketchup and white bread were carried out. The main conclusion is that LCA is very valuable for incorporating environmental aspects in the development of more sustainable food systems. One of the major problems encountered was the great scarcity of environmental data. It was found that there is a need for simplified methods that can be used as a compass to show the direction towards sustainability. Accordingly, the feasibility of combining the concept of sustainability principles and LCA for product development was examined and discussed. This combination was found to yield a simplified method well suited for screening analysis and product development.

Keywords: Bread; environmental analysis; food; ketchup; LCA; Life Cycle Assessment; sustainability principles

Introduction

The purpose of this paper is to summarise the most important findings and experiences of my Ph.D. studies carried out at SIK, The Swedish Institute for Food and Biotechnology, between 1993 and 1998 (ANDERSSON, 1998). The background of my research project is that the food industry in the early 1990s expressed a wish that SIK, which is an industrial research institute, should start a project with the aim of learning more about the feasibility and limitations of applying LCA to food products. Since the methodology was originally developed for industrial products, this was a relevant objective for a research project. A pre-study was carried out at SIK during 1992 and after a successful application to the Swedish Waste Research Council I was employed to carry out the work.

Why studies of the environmental impact caused by food products? In the rich part of the world, there is a growing awareness that the present food consumption patterns are neither sustainable nor healthy. Where life styles are concerned, there are many services and products we can manage without; although food will always be a necessity. Therefore, the future systems for food production and consumption need to be based on a global, ecological view; minimal environmental impact and efficient utilisation of natural resources must be made important criteria in the development of food products and the selection of food systems. As discussed by Wackernagel and Rees (1996), the human economy is a fully dependent sub-system of the ecosphere and a basic understanding of our ecological constraints is a prerequisite for effective and liveable sustainability strategies. This is a core issue; as a consequence of the cultural ethic prevailing in most parts of the world, people generally tend to see society as more or less independent of nature.

For Sweden, it has been estimated that the system for production and consumption of foods requires approximately 17 per cent of the total energy use (UHLIN, 1997). A similar share of energy use of the food system has been estimated for the Netherlands and the U.S. by Wilting (1996) and SINGH (1986), respectively. The use of energy leads to emissions and negative environmental impact. In a Danish study of a family with two children, one third of the family's total environmental impact was found to be related to the food system (FORBRUGERSTYRELSEN, 1996).

Besides energy, other important resources needed in the food production system are land, water and nutrients. At present, there is a surplus of farm land both in Sweden and in the European Union. However, taking into consideration the international trade in agricultural raw materials and products, estimates made by Lehmann et al. (1995) indicate that the EU countries are using approximately 131 000 km^2 of arable land in other parts of the world (equivalent to 70 per cent of the total arable land in France). This situation is not a new phenomenon: it was discussed as early as 1971 by Borgström who coined the term ghost acreage. From a global perspective, both land suitable for farming and water are already limited resources; if we want a transition to an energy system based on a larger share of biofuel and an agriculture based on a larger proportion of organic cultivation, the demand for these two resources will be even greater. The population growth and changes in food consumption patterns threaten to worsen the situation.

Nutrients such as nitrogen, phosphorous and potassium are essential inputs to agricultural production. The concept of chemical fertilisers was developed in the late 19th century to compensate the agricultural soils for the losses of nutrients. Fertilisers are easier to transport than latrine and organic waste. The new technique, which turned latrine matter into a waste product, helped to make impoverished soils fertile again. However, raw phosphate is a limited resource and contains varying amounts of toxic substances such as cadmium and arsenic. Nitrogen can be fixed from the air, but the process requires relatively large amounts of energy. Thus, a relevant criterion for more sustainable systems is

that the flows of nutrients be cyclic (so that the consumption of fertilisers can be decreased); efforts must be made to develop practical and hygienically safe systems in which these flows are not contaminated.

As stated by Wackernagel and Rees (1996), 'the first step toward a more sustainable world is to accept ecological reality and the socio-economic challenges it implies'. To achieve a more sustainable society, tools to evaluate strategies and monitor progress are required. One such tool is LCA, but there are also other methods under parallel development. So far, there have been only a few LCAs that attempted to cover an entire food system. Parts of food systems have, however, been studied in LCAs on a wide variety of food products. I choose not to mention any of these studies here, but the results and findings of some of them are discussed together with the findings of my own work. For an overview of LCAs of food products, see for example Jungbluth (2000), Andersson (1998) and Andersson et al. (1994).

To reduce the negative environmental effects and to avoid sub-optimisations, system analysis studies are needed, starting with simple products to begin with and, as knowledge is gained and the methods are improved, shifting to more complex products and whole diets. Two case studies were conducted within the project. Tomato ketchup was studied to obtain information on the magnitude and interrelations of the environmental impact of the different life cycle steps (Andersson et al., 1998a) and to identify options for improvements (Andersson & Ohlsson, 1999a). White loaf bread was studied to compare the environmental effects of baking on different scales (Andersson & Ohlsson, 1999b). Finally, the feasibility of combining the LCA methodology and the concept of sustainability principles was examined (Andersson et al., 1998b).

1 Objectives

- The overall objectives of my Ph.D. studies were the following:
- To learn more about the feasibility and limitations of applying the LCA methodology to food products and food production systems; and
- To generate, for food systems, information on: (1) the magnitude and interrelations of the environmental impact of the different life cycle steps (or, in other words, what is big and small in the life cycle of food products from an environmental point of view and are there any connections between the degree of environmental impact caused by the different processes in a food system); (2) the methodological issues and parameters of particular importance; and (3) the influence of systems-related issues such as scale of production, geographical location and distribution.

2 Methods

Two case studies were conducted to begin fulfilling the objectives. The products chosen for the case studies were **tomato ketchup** and **white loaf bread**. Important criteria in the choice of products were that the product system should be simple and raise relevant systems-related issues. Tomato ketchup was chosen because its life cycle represents a rather common food-product system: it includes a harvest, a preservation process (seasonal production), storage, transportation and, finally, further processing into a consumer product. Bread was chosen because it is an important staple food and offers the interesting comparison of baking on different scales.

2.1 Goals

The case study of tomato ketchup had three primary goals. The first was to conduct a screening LCA in order to: obtain information on the magnitude and interrelations of the environmental loads from the different life cycle steps; identify the parts of the life cycle that give rise to the most significant environmental impact; and point out major gaps in the available data (Andersson et al., 1998a). The second goal was to compare alternative packaging systems for ketchup. The existing packaging system of plastic bottles was compared with a hypothetical one of glass bottles (Andersson, 1998). The third was to carry out an improvement assessment in order to: illustrate how LCA can be used in production development by the food industry; investigate the influence of the geographical location of certain processes; and find ways to improve the product's environmental performance (Andersson & Ohlsson, 1999a).

For the case study of bread (Andersson & Ohlsson, 1999b), the goal was to compare bread produced on different scales. The scales compared are: home baking, a local bakery and two industrial bakeries with distribution areas of different sizes.

2.2 The systems investigated

The systems studied in the screening LCA of ketchup and in the comparative LCA of bread are described schematically in **Fig. 1** and in more detail in **Table 1** and **Table 2**. The ketchup studied is one of the most common brands of tomato ketchup sold in Sweden; it is marketed in 1 kg red

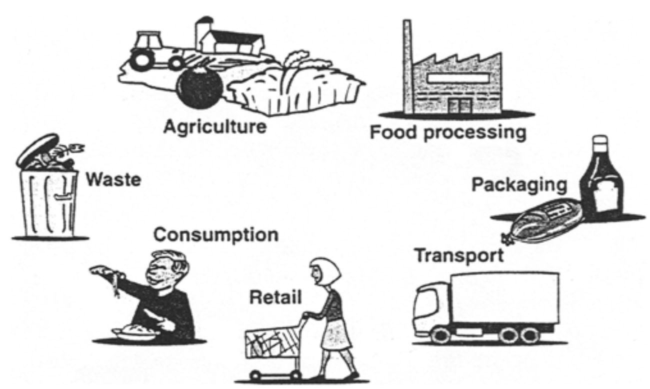

Fig. 1: A simplified description of the life cycle of food products. Note that, for nutrients and organic matter, the systems studied are more linear than cyclic. Thus, the flow from waste to agriculture could have been omitted.

Table 1: The ketchup sub-systems, the processes included and the scenarios investigated in the screening LCA.

Sub-system	Processes included	Scenarios
Agriculture	• Cultivation of tomatoes and sugar beets. • Production of inputs to the cultivation steps.	
Food Processing	Production of tomato paste, raw sugar, sugar solution, vinegar, spice emulsion, salt and ketchup.	
Packaging	Production and transportation processes included in the packaging systems for tomato paste and ketchup.	<u>Waste management</u>: 1. Landfill 2. Material recycling and /or incineration with energy recovery
Transportation	All transportation processes except for the transports included in the packaging sub-system.	
Consumer Phase	• Transportation from retailer to household (shopping). • Storage of ketchup bottle in refrigerator.	<u>Storage time</u>: A. One month B. One year

Table 2: The bread sub-systems, the processes included and the scenarios investigated.

Sub-system	Processes included	Scenarios
Agriculture	• Cultivation of wheat. • Extraction of raw materials and production of fertilisers.	
Food Processing	• Milling of wheat. • Baking of bread. • Cleaning in the bakeries and washing dishes in conjunction with home baking.	<u>Home baking</u> Water used for washing dishes heated by: • electricity (el.) • oil
Transportation	All transportation processes except for the transports included in the packaging sub-system and the process of shopping.	
Packaging	Production and transportation processes included in the packaging systems for bread ingredients and bread.	<u>Waste incineration</u> Avoided emissions assuming the following heating alternatives are used: A. oil B. biofuel
Consumer Phase	• Transportation from retailer to household (shopping). • Storage of bread in freezer.	

plastic bottles. The type of bread studied is white loaf bread baked in pans. – The scales compared in the case study of bread are the following:

- Industrial Bakery 1 with Sweden as the distribution area is referred to as Industry 1 or the large industrial bakery. (The total annual production is approximately 30 800 tonnes and the capacity of the specific production line with a tunnel oven is 1 700 kg bread per hour).
- Industrial Bakery 2 with a region as the distribution area is referred to as Industry 2 or the small industrial bakery. (The total annual production is approximately 12 800 tonnes and the capacity of the specific production line with a tunnel oven is 1 000 kg bread per hour).
- The local bakery has an annual economic turnover of 3.6 million SEK (470 000 US$) and uses a rack oven. The total annual production is not known.
- Home baking was for three loaves of bread (approximately 2 kg) baked at one time.

To carry out the *improvement assessment* (the third goal of the ketchup study), six alternative systems (including the food processing, packaging and transportation sub-systems) were modelled, simulated and compared with the current system. The systems studied are the following (for a more detailed description, see ANDERSSON & OHLSSON, 1999a).

- The A1 system is the system producing the current product. Tomatoes are cultivated in the Mediterranean countries and processed into tomato paste that is transported by sea to Sweden for further processing into ketchup.
- The A2 system differs from the current product system in that: calor gas (instead of heavy fuel oil) is used for the production of tomato paste; the tomato paste is transported by train (instead of by sea) to Sweden; and the ketchup is distributed by train (instead of by lorry).
- The B system is the production of ketchup and a less concentrated tomato paste in the same plant. The production of tomato paste is seasonal, the paste is stored aseptically in large tanks and ketchup is produced all

year. Calor gas is used for the production of both tomato paste and ketchup.
- The C system is the same as B, except that the tomato paste is used directly in the production of ketchup. Thus, the paste need not be sterilised.
- The D1 system is for ketchup that is produced in Sweden using a less concentrated tomato paste transported to Sweden by road tanker.
- The D2 system differs from the D1 only in that the paste is transported by train.
- The D3 system differs from the D1 in that: calor gas (instead of heavy fuel oil) is used for the production of tomato paste; the tomato paste is transported to Sweden by sea; natural gas (instead of coal) is used for the production of sugar; and the ketchup is distributed by train (instead of by lorry).

2.3 The functional units

For ketchup, the functional unit (FU) was defined as 1 000 kg of ketchup consumed, assuming a five per cent loss in the consumer phase. For bread, the functional unit was defined as 1 kg of bread, including storage in the households, but excluding losses in the consumer phase.

2.4 The LCA methodology

The case studies were conducted before there were any ISO standards on LCA. To be brief, the methodology applied is LCA as described by Lindfors et al. (1995). For details, I refer to Andersson (1998). Important to note is that specific systems have been analysed in both case studies using a combination of specific and general data. Therefore, general conclusions must be drawn with care.

3 Results

This section presents and explains some of the results from the case studies. The simplified method outlined combining the LCA methodology and the concept of sustainability principles (Andersson et al., 1998b) is presented in brief.

3.1 The relative significance of different life cycle steps

The relative, environmental significance of different life cycle steps varies among different food products. For ketchup, the relative contributions made by the sub-systems included in the screening LCA, as well as the absolute, total contributions, are summarised in **Table 3**. The food processing and packaging sub-systems were found to be hot spots for most, but not all, of the impact categories investigated. For the impact categories of eutrophication, human toxicity and ecotoxicity, it is clear that the agriculture sub-system is highly significant, even though neither leakage of nutrients from the fields nor application of pesticides were included quantitatively in the impact assessment (due to lack of data). The consumer phase was found to be of significance in the use of primary energy and photo-oxidant formation: in the energy

Table 3: The relative contributions made by the sub-systems included in the screening LCA of ketchup and the absolute, total contributions (Andersson, 1998). Here, for packaging, weighted average values are presented for the two waste management scenarios (42 per cent to landfill and 58 per cent to incineration). The consumer phase includes the household phase and shopping. The functional unit (FU) is defined as one tonne of ketchup consumed.

	Agriculture [%]	Food processing [%]	Packaging [%]	Transportation [%]	Consumer phase [%]	Total [per FU]
Primary energy	7[a] / 4[b]	39[a] / 22[b]	36[a] / 21[b]	5[a] / 3[b]	13[a] / 50[b]	18[a] / 32[b] GJ
Global warming:						1 100 kg CO_2-equiv.
Time frame 100 years	14	41	24	9	12	
Acidification:						220 mol H^+
Maximum	17	53	6	20	4	
Eutrophication:						71 kg O_2
Maximum	69	12	5	12	3	
Photo-oxidant formation:						
NO_x	25	24	11	32	8	4.4 kg
VOCs [c]	16	19	33	4	29	1 010 g ethene-equiv.
Human toxicity:						8.2 kg [d]
CML	15	55	6	19	5	28 000
Tellus	100	–	–	–	–	
Ecotoxicity:						3 600 m^3
Water	5	19	73	2	2	8 600 kg
Soil	100	–	–	–	–	
Radioactive waste	–	52	48[a] / 47[b]	–	–[a] / 1[b]	36 cm^3

[a] The consumer phase includes storage of the ketchup bottle for one month in a refrigerator.
[b] The consumer phase includes storage of the ketchup bottle for one year in a refrigerator.
[c] Assessed by using peak ozone data (Heijungs et al., 1992a).
[d] The unit is kg body weight.

use, the storage time in a refrigerator was a critical parameter; and for photo-oxidant formation the high contribution is due to carbon monoxide from the process of shopping (due to the assumption of car use for a share of the shopping trips). Although the findings are specific for the tomato ketchup studied, similar results could be expected for products with similar life cycles, for example jam and juices.

3.2 The influence of scale of production

Some of the results of the comparative LCA of bread is presented in **Fig. 2**. When evaluating the results, it is important to remember that the systems compared are models of specific, existing systems. It is clear that the Industrial Bakery 1 system uses more primary energy and contributes more to global warming, acidification, eutrophication and photo-oxidant formation than all of the other systems. As regards the scale of production, the results suggest that there may be a breaking point somewhere between Industry 1 and Industry 2. The baking in Industrial Bakery 1 could surely be made as energy efficient as that in Industrial Bakery 2. The question is whether the distribution area for Industry 1 is too large (Sweden is a country with long distances and is not densely populated). The home baking system shows a relatively high requirement for energy and water; otherwise, the differences between home baking, the local bakery and the small industrial bakery are negligible. For land use, the systems using a greater share of winter wheat are more efficient as higher yields can be obtained.

3.3 The influence of geographical location

The results of the simulations for the alternative systems studied in the improvement assessment of ketchup are given in **Table 4**. It was found that: (1) the current geographical location of the production of ketchup is preferable; (2) the contributions to acidification can be reduced significantly; and (3) the environmental profile of the product can be improved for either the type of tomato paste currently used (the A2 system) or a less concentrated tomato paste (the D3 system). A shift to a less concentrated paste would also mean that traditional quality parameters of the ketchup, such as colour and consistency, could be improved.

3.4 A simplified LCA method including sustainability aspects

When starting from the present production system, it can be very difficult to achieve major reductions of negative environmental impact. Characterisation results for the impact categories included can point in different directions, as can

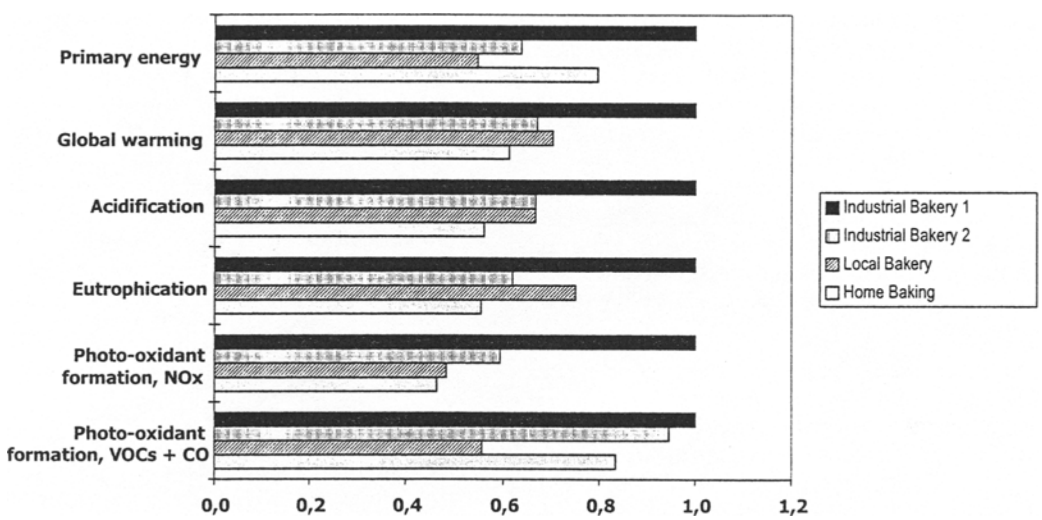

Fig. 2: Some results from the case study of bread. The energy use and the potential contributions to some environmental effects made by the systems of Industrial Bakery 2, Local Bakery and Home Baking as compared to the energy use and the contributions made by Industrial Bakery 1.

Table 4: Quotients between the contributions of the alternative systems and the current system A1 (Andersson & Ohlsson, 1999a). Values lower than 1 indicate improvement and values higher than 1 changes for the worse.

Impact category	A2	B	C	D1	D2	D3
Primary energy	1.02	0.95	0.91	0.91	0.90	0.88
Global warming, time frame 100 years	0.94	1.11	1.06	0.94	0.89	0.81
Acidification, maximum	0.42	0.79	0.78	0.82	0.72	0.53
Eutrophication, maximum	0.64	1.11	1.08	0.96	0.73	0.88
Photo-oxidant formation:						
NO_x	0.62	1.14	1.11	0.97	0.69	0.89
VOCs and CO	0.78	1.08	1.08	0.95	0.99	0.67
Radioactive waste	1.22	0.45	0.45	0.89	1.06	1.02

valuation results, when multiple valuation methods have been applied. When improvements are made for one life cycle step, changes for the worse often occur somewhere else in the life cycle. Consequently, for longer-termed development aiming at sustainability, it is necessary to search for completely new solutions. This is why the feasibility of combining the concept of sustainability principles and the methodology of LCA was examined and discussed (ANDERSSON et al., 1998b). The aim was to achieve an operational tool that can be used to incorporate both the sustainability and life cycle perspectives in strategic planning, screening analyses and the development of products and processes.

As criteria for sustainability, the four Socio-Ecological Principles formulated by Holmberg et al. (1996) were chosen. These principles are listed below and the practical implications are explained briefly:

- *Principle 1: Substances from the lithosphere must not systematically accumulate in the ecosphere.* In practical terms, this means that the use of fossil fuels and mining (especially of scarce metals) must be radically decreased.
- *Principle 2: Society-produced substances must not systematically accumulate in the ecosphere.* In practical terms, this means that both the intentional and unintentional production of natural substances that can accumulate must be decreased. The use of persistent substances foreign to nature must be phased out.
- *Principle 3: The physical conditions for production and diversity within the ecosphere must not be systematically deteriorated.* In practical terms, this means much more efficient and careful use of areas productive for agriculture, forestry and fishing. Likewise, infrastructure needs to be more carefully planned.
- *Principle 4: The use of resources must be efficient and just with respect to meeting human needs.* In practical terms, this means increased technical and organisational efficiency as well as a more just distribution of resources, including more resource-efficient lifestyles for the rich part of humankind.

The method outlined has the structure of LCA; the Socio-Ecological Principles have been incorporated for each of the main steps: goal and scope definition, inventory analysis, impact assessment and improvement assessment. Socio-Ecological Principle 3, about the physical conditions for biological production and diversity, and Principle 4, concerning an efficient and fair use of resources, make the perspective wider than that of traditional LCA. The analysis and results can be either qualitative or semi-quantitative. To illustrate our approach to the LCA methodology, selected parts from the case study of tomato ketchup are used.

The goal definition of the ketchup example is to identify the changes necessary to devise a more sustainable product which will be competitive in the long run. In the inventory analysis, as in traditional LCA, the system under study is defined and a flow chart illustrating the processes included is prepared. In the next step, energy and material flows are identified as well as ecosystem manipulations and issues raised by Principle 4. The impact assessment uses a qualitative approach; potential hot spots are identified for each Socio-Ecological Principle. For Principles 1 and 2, a grading system was proposed. For Principles 3 and 4, potential hot spots are examined qualitatively, since criteria for grading have not yet been formulated. Principle 4 raises questions about the product and the system that should be taken into consideration, preferably during the goal definition, so that sub-optimisation can be avoided. For the improvement assessment, general guidelines are summarised.

4 Discussion

4.1 The relative significance of different life cycle steps

It was observed in the screening LCA of ketchup that the packaging and processing in food industries are significant in the total environmental impact made by ketchup. For the impact categories of eutrophication, human toxicity and ecotoxicity, the agricultural production was found to be a hot spot. For primary energy use, the storage time in a refrigerator (household phase) is a critical parameter. For bread it was found that the agriculture sub-system contributes significantly to all of the environmental effects included in the impact assessment.

As mentioned above, very few food studies have attempted to include the whole life cycle; the sub-system most often omitted is the consumer phase. According to energy analyses of potatoes, meatballs and chicken, the agricultural production and consumer phase are hot spots; for French fries, the food processing and consumer phase are hot spots (JOHANNISSON & OLSSON, 1997). Also for beer, the consumer phase has been reported to contribute significantly (PETER, 1996). For meat, the agriculture sub-system dominates with regard to the energy requirement, emissions of the greenhouse gases carbon dioxide and methane, and the contribution to eutrophication (MØLLER, 1997). Similarly, for milk, the agriculture sub-system dominates in emissions of carbon dioxide and methane as well as contribution to eutrophication (MØLLER & HØGAAS, 1997).

4.2 The influence of systems-related issues

The bread study made it clear that, when studying specific, existing systems, there are several aspects that may influence the results more than the scale of production. Generally, four aspects were found to be important when comparing systems for production and consumption of bread:

- the energy efficiency and the source of energy used for baking;
- the distances and logistics involved in the distribution of the bread;
- the behaviour of the consumer in conjunction with shopping (the method of allocation and assumptions associated with car use, distance and amount bought); and
- the yield of grain and the leakage of nitrogen from the fields, both of which depend on the type of grain (for example winter or spring wheat) and the cultivation site.

A similar bread study has been carried out by Probst (1998). The findings listed above are in line with the ones of Probst. An important difference between our studies is that Probst found no breaking point corresponding to the one found in

my study (between the Industry 1 and Industry 2 systems). This difference can probably be explained by the distances and logistics involved in the distribution of the bread (Sweden as the distribution area means long distances). For milk, a study with a similar goal definition has been reported by Høgaas Eide (1998); as for the bread study reported here, her results show that when studying specific, existing systems there are several aspects that may influence the results more than the scale of production.

One of the findings of the improvement assessment of ketchup is that the current geographical location of the production is preferable. The aspect of geographical location has been studied also for apples (Stadig, 1997) and the transportation was found to be of relatively high significance in both energy use and the environmental effects related to it. The apple study included also an assessment of the pesticides applied; the overall conclusion was that, for consumption in Sweden, Swedish apples are clearly preferable.

4.3 Special demands on methodology

As mentioned above, the LCA methodology was first developed for industrial products and manufacturing systems; the application to systems including agriculture, fishery and forestry makes some special demands on the methodology. Examples of critical methodological issues that need some special consideration when dealing with food systems are the definitions of system boundaries and functional unit, as well as allocation procedures. The system boundary should ideally be the boundary between the technological system and nature; however, primary production of foods and other renewable resources takes place in nature itself. Thus, the impact category of land use is central and needs to be further defined; principles for how this can be done have been discussed by Sas et al. (1997), Mattsson et al. (1998) and Lindeijer et al. (1998) among others. For agricultural production, the boundary between production and capital goods (machines and buildings) has been found to significantly influence the results (Weidema et al., 1995). In LCA studies, data for a given crop is usually desired. Since a crop can benefit from either the previous crops or the inputs applied for previous crops, crop rotation can influence the results. By system expansion, the complete crop rotation can be studied, but allocation is then necessary. Allocation is also necessary to partition the environmental loads of farming between, for example, beef and milk. Likewise, the environmental loads caused by storage and handling of manure needs to be allocated among, for example, beef, milk and the crop fertilised by application of manure. Allocation for these products has been conducted by Cederberg (1998) and Møller & Høgaas (1997).

For foods, the function and the functional unit can be defined in many different ways and the choice of definition can significantly influence the conclusions of an LCA study. Examples of parameters of relevance are the contents of various nutrients and fibres, the caloric value, shelf-life, taste, smell and appearance (for example colour and consistency). A minimum requirement must be that the foods are hygienically and toxicologically safe (toxins formed by microorganisms, residues of pesticides and cadmium from fertilisers). The proper definition of the functional unit depends on the goal of the study. If the purpose is a screening LCA of a specific product, the functional unit is not as critical as if the goal were to compare different products. When comparing various food products, it seems relevant to take into consideration their role or function in the diet, for example the vitamins for fruits and vegetables and the content of proteins for meat and fish. Another approach is to compare complete meals or diets that fulfil given nutritional demands. Carlsson-Kanyama (1998) has compared both a set of different functional units and one of alternative meals.

Collection of representative data is a difficulty encountered especially when dealing with agricultural production and the consumer phase. It is often hard to link available statistics to a given crop or a specific product. Models to estimate the leakage of nutrients and pesticides in cultivation, for different soils, climates and crops, are needed in LCAs of food products; likewise models to assess toxicity need to be further developed. The consumer phase has been studied very little; studies of the behaviour of consumers in conjunction with shopping, storage of foods and household work related to foods need to be documented in more detail.

A step not yet included in LCAs of foods is waste management of human excrement. The relevance of including this step depends on the goal of the study; for a study aiming at closing the nutrient flows and identifying the best options to do so, this step is highly relevant. For a study of a specific food product, it is not yet possible to include this step, and for a study comparing similar products it may not be necessary.

4.4 Key parameters and significant issues

Detailed studies and a systems approach, for different types of food products, are useful to identify parameters and issues of high significance. So far, the application of LCA to food products has revealed the following parameters and issues to be significant in relation to the environmental performance (my own case studies and other LCAs of food products, see Andersson, 1998 for more detail).

- *The use of energy* has often been employed as an indicator of environmental impact. Although the results presented illustrate the complexity in a scientific evaluation of a product's environmental performance, the energy requirement in combination with information on the sources of primary energy is a useful indicator of environmental impacts such as global warming, acidification, photo-oxidant formation and the generation of radioactive waste. Most of the key parameters identified can be related to energy use and certain types of energy sources.
- Examples of *non-energy-related emissions* identified as key parameters in food LCAs are: emissions of nitrous oxide from the production of nitrogen fertilisers and from the fields; emissions of methane from cattle and rice fields; leakage of refrigerants; losses of ammonia from farmyard manure; leakage of nitrogen and phosphorous; and, for bread, ethanol formed during baking. For the impact categories photo-oxidant formation and eutrophication,

the significance of these emissions can be equal to or greater than those related to energy use.

- For *toxicity*, the impact of pesticides is a key issue in LCAs of food products. Efforts must be made to investigate how the use of pesticides can be minimised, for example: by adopting well planned crop rotations; using species well suited for the specific area of cultivation; and crop variety in the agricultural landscape. The current use of mineral fertilisers produced from raw phosphate leads to contamination of the agricultural soils with toxic substances such as cadmium, arsenic and zinc. Using sewage sludge as an input to cultivation would help to bring about a cyclic flow of nutrients; however, to decrease the risk of toxic contamination, new solutions for handling of organic waste and waste water are required.
- Essential *resources* for food production are land, water, nutrients and biodiversity. Globally, arable land is a limited resource. Water use is significant since, in many areas, clean water is already, or is expected to be, a limited resource. In addition, the use of water is often related closely to the use of energy (for heating and pumping). The handling of nutrients and organic waste is a central and systems-related issue, both on the resource side, as for phosphorous, and on the effect side. Biodiversity (different ecosystems, species and genes) is valuable both directly as a resource base for cultivation and husbandry, and indirectly for the support systems.

4.5 The feasibility of including sustainability in LCA

The simplified method outlined is based on a model of sustainability; this is a strength that the current valuation methods used in LCAs lack. Although the valuation methods also aim at environmental improvements, they are tied to economic and political issues (since they are based either on willingness to pay or political targets). The questions raised by Principle 4 are necessary to avoid sub-optimisation which can be a consequence of using the present production system as a starting-point. Since the method proposed concentrates on effects early in the complex cause-and-effect chain, it also gives guidance about substances for which environmental effects are not yet known. The qualitative or semi-quantitative approach has both advantages and drawbacks. Although a semi-quantitative analysis is less time consuming and costly, it can still highlight the important issues. It also eases the inclusion of qualitative information, as well as aspects not usually included because they are difficult to quantify; for foods, such aspects and information are often of major significance. On the other hand, quantitative information may be overlooked. Special care should be taken to avoid missing the significance of large flows of substances when the substances themselves are graded (according to the grading system proposed for Principle 1 and Principle 2) as not very likely to damage the environment. (As an example, carbon dioxide has a relatively low global warming potential as compared to substances such as methane and nitrous oxide. The emissions of carbon dioxide, however, are usually very large.) In order to compare products and systems, quantitative methods are required; to make the method outlined quantitative, priorities must be assigned for both the Socio-Ecological Principles and the LCA impact categories. However, for the applications intended, product development aiming at sustainability and screening analysis, the method presented can be useful.

For ketchup, potential hot spots were identified using the method outlined. Based on the ketchup example and LCA studies of other food products, some general conclusions can be drawn for food production systems:

- For Principle 1, the use of fossil fuels such as oil, gas and coal is a hot spot; in the rich part of the world, the whole food production system is heavily dependent on fossil fuels for fertilisers, pesticides, agricultural machines, irrigation, transportation and further processing. Another hot spot is the cadmium originating from the phosphate rock used in fertiliser production.
- For Principle 2, examples of hot spots are: energy related emissions such as sulphur dioxide, hydrocarbons and, due to the relatively large amounts, carbon dioxide; leakage of pesticides and their degradation products; emissions of nitrous oxide occurring both in the production of nitrogen fertilisers and from the fields after application; leakage of refrigerants such as CFC-11; and wasted flows of phosphorous.
- For Principle 3, manipulation of ecosystems and harvesting, both of which threaten long term productivity and biodiversity, are hot spots. Examples include: the too intense cultivation practices that threaten to deplete ground water tables in parts of the U.S. and China; the over harvesting of certain fish species; and the current use of pesticides, fertilisers and heavy agricultural machines. The dependence of humankind on the long-term functions of the ecosystems will become more obvious when the use of fossil fuels and uranium is reduced.
- For Principle 4, even though a specific food product cannot be said to fulfil an essential human need, it could still fit to a sustainable society, provided that the existing product system is modified according to Principles 1 to 3 and that the organisational and technological efficiencies are improved. The consumption patterns are then assumed to be included in the category of organisational efficiency.

5 Conclusions and Future Outlook

The main conclusion is that Life Cycle Assessment is very valuable for incorporating environmental aspects in the development of more sustainable systems for the production and consumption of foods. For example, LCA is an excellent tool for learning and for increasing the environmental awareness of companies as well as of society in general. The results anticipated from the LCA method, however must be reasonable; there are questions that LCAs cannot yet answer. For example, toxicological issues and local environmental effects are difficult to include in the type of LCA currently in use. There are also other concepts for environmental assessment of production systems under parallel development; care should be taken to choose the most suitable method or combination of methods for each specific application.

From the work with the case studies, the following conclusions were drawn:

- For foods, methodological difficulties are encountered especially in the analysis of agricultural production. Otherwise, the difficulties are very much the same as for other types of product systems.
- Acquisition and evaluation of environmental data was the most time consuming phase of the case studies. It was found that the food industry has a poor knowledge of the energy requirement of specific production lines; measured data are rare. Likewise, for emissions, measured data are rare and available at best for a very limited number of substances for the plant as a whole.
- For ketchup, the geographical location of given life cycle steps was found to influence the results, not only due to the varying demands for transportation but also due to the varying environmental loads related to the generation of electricity. For bread, it was found that when studying specific existing systems, there are several aspects that may influence the results more than the scale of production.
- Sensitivity analyses show that the uncertainties are large. Therefore, appropriate ways to use the results are: (1) to get a rough picture of magnitudes and interrelations with regard to life cycle steps and parameters; and (2) as a platform for future studies.

To summarise some more detailed conclusions from the case studies, it was observed in the screening LCA of ketchup that the packaging and processing in food industries are significant in the total environmental impact made by ketchup. From the improvement assessment of ketchup, it was concluded that: (1) the current geographical location of the production of ketchup is preferable; (2) the contribution to acidification can be reduced significantly; (3) the environmental profile of the product can be improved for either the type of tomato paste currently used or a less concentrated tomato paste; and (4) none of the plastic and glass bottle packaging systems compared for ketchup is clearly better than the other.

For bread, the Industrial Bakery 1 system was found to use more primary energy and contribute more to global warming, acidification, eutrophication and photo-oxidant formation than all of the other systems. The home baking system shows a relatively high requirement for energy and water; otherwise, the differences between home baking, the local bakery and the small industrial bakery were found to be negligible.

Generating information on the magnitude and interrelations of the environmental impact of different life cycle steps (screening analysis) is an excellent way to use the LCA method. It allows for treating life cycle steps as black boxes (that is detailed or measured data are not necessarily required) and for employing generic data. Generally, for foods, it can be concluded that the systems perspective is of utmost importance. To emphasise only transportation and packaging, as sometimes happens in public debate, may lead to sub-optimisations. The significance of a given life cycle step varies greatly for different types of food products. So far, the application of LCA to food products has revealed the following parameters and issues to be significant in relation to the environmental performance:

- the use of energy;
- non-energy-related emissions (such as nitrous oxide, methane and ammonia);
- the use of pesticides and mineral fertilisers (toxicity); and
- resources such as land, water, nutrients and biodiversity.

For LCAs to be conducted routinely, there are at least four prerequisites: (1) data bases comprising well-documented environmental data for common inputs to agriculture and common food ingredients; (2) case studies of various staple foods to generate data for the data bases and to identify the key parameters and effects of methodological choices; (3) statistics for average consumer behaviour and agricultural practises for different regions; and (4) interdisciplinary work to improve the modelling of the different parts of the food system.

Measurements of energy use and emissions are necessary both to improve the models and to identify options for improvements. As the use of LCA and other concepts for environmental assessment is increasing, the research and development are likely to involve more experimental studies. Research on life styles and how to communicate environmental qualities of products and services will also be required.

The work reported in my dissertation should be seen as one small part of the efforts required to ease the use of LCA for food systems and to adjust and develop the method. Until the prerequisites above are fulfilled, there is a need for simplified tools for qualitative and semi-quantitative analyses. The combination of the concept of sustainability principles and the methodology of LCA yields a method well suited for screening analysis and product development aiming toward sustainability. Most important are that the method outlined: (1) incorporates the sustainability perspective; (2) captures aspects and parameters highly relevant for foods, but often omitted from traditional LCAs since they are difficult to quantify; and (3) is less time consuming. At the moment, appropriate environmental management offers companies a way of being competitive; in the near future, it will probably be a prerequisite to remaining in the market. LCA is one of several concepts useful for environmental management and life cycle thinking is a good way to get the sustainable development started.

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